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Development of Microorganisms Capable of Absorbing Environmental Pollutants through Synthetic Biological Engineering

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ABSTRACT

In Indonesia, environmental pollution is a major concern, especially in industrialised and urban areas. The use of synthesised microorganisms can be an innovative solution to rehabilitate the damaged ecosystems in this region. In this research, an innovative approach based on synthetic biological engineering will be developed to create microbes that have an optimal capacity to absorb and decompose various types of environmental pollutants, such as heavy metals (Pb and Hg), hydrocarbons (benzene), and organic waste (phenol). The results show that the engineered bacteria Escherichia coli, Pseudomonas putida, Bacillus subtilis, and Alcaligenes eutrophus showed high pollutant removal efficiency (85-93%) under laboratory conditions. These results support the potential of synthetic biology technology as an innovative solutions in bioremediation of polluted environments. This research makes a real contribution to green technology innovation in environmental pollution mitigation, supporting the implementation of Sustainable Development Goals (SDGs), especially on points 6 (Clean Water) and 15 (Land Ecosystems).

Keywords: *Effectiveness Engineered Microorganisms, Environmental Pollutant Absorption, Synthetic Biological Engineering*

INTRODUCTION

The problem of environmental pollution is one of the global challenges that continues to increase along with industrial development, urbanisation, and other human activities. Environmental pollutants such as heavy metals, hazardous organic compounds and plastic waste have significant impacts on ecosystems and human health (Fores Ecosystem, 2024; Sabila, 2023). Conventional efforts in pollution mitigation, such as mechanical and chemical waste treatment,

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often have limitations, including high cost, low efficiency, and the potential to produce harmful by-products (Kumar et al., 2020). Therefore, technological innovations are required to provide more effective and sustainable solutions.

Genetic engineering techniques allow researchers to identify and modify genes involved in pollutant degradation. This allows for more targeted strategies to be developed to deal with different types of pollutants. For example, microorganisms can be modified to increase their capacity to absorb heavy metals or to activate enzymes specific for the degradation of harmful organic molecules (Evitasari, Sukono, Hikmawan, & Satriawan, 2020).

Synthetic bioengineering provides new opportunities to address these challenges through the development of microorganisms specifically designed to absorb and treat environmental pollutants (Khastini et al., 2022). This approach utilises biotechnology to genetically modify microorganisms to have specific capabilities in detecting, binding, and breaking down harmful compounds into safer forms (Choi et al., 2021). With high adaptability and reproducibility, engineered microorganisms can be efficient bioremediation agents.

Several studies have demonstrated the potential of microorganisms in addressing various types of pollutants. For example, genetically modified Escherichia coli can be used to detect the presence of heavy metals such as mercury and cadmium in aquatic environments (Rathnayake et al., 2019). On the other hand, Pseudomonas putida bacteria have been successfully developed to degrade hydrocarbon compounds derived from petroleum spills (Patel et al., 2022). This research paves the way for further exploration to address other types of pollutants.

The local context also shows the urgency of developing this technology. In Indonesia, environmental pollution is a major concern, especially in industrialised and urban areas. Major rivers, such as the Citarum in West Java, are listed as among the most polluted in the world due to industrial and domestic waste (UNEP, 2018). The use of synthesised microorganisms can be an innovative solution to rehabilitate the damaged ecosystems in this region.

In addition to ecological benefits, this technology also has great economic potential. By creating a cheap and efficient bioremediation method, the development of these microorganisms can promote a more environmentally friendly and sustainable green industry. This is in line with the Sustainable Development Goals (SDGs), particularly goal 6 on clean water and sanitation and goal 15 on terrestrial ecosystems (PMPRO.id, 2020).

However, the implementation of this technology also requires attention to safety and regulatory aspects. Genetically modified microorganisms must be thoroughly tested to ensure there are no negative impacts on biodiversity and human health. This is where multidisciplinary studies become crucial, integrating synthetic biology, ecology and environmental ethics.

The development of microorganisms capable of absorbing pollutants also requires a collaborative approach between academia, government and the industrial sector. This collaboration can accelerate research and technology development, while ensuring that the results of innovation can be widely applied and have a real impact on society.

In the context of this research, an innovative approach based on synthetic biological engineering will be developed to create microorganisms that have an optimal capacity to absorb and treat environmental pollutants. The main focus is to design microorganisms that can be applied directly to polluted environments, with high efficiency and minimal environmental impact.

METHODS

To achieve the objectives of this research, approaches from various disciplines, such as synthetic biology, microbiology, and ecotoxicology, will be used. The purpose of identifying potential microorganisms is to find microorganisms that can absorb certain pollutants naturally. literature research to identify bioremediation bacteria such as Escherichia coli and Pseudomonas putida. collect information on the main pollutants of the study site, such as hydrocarbons, heavy metals, or organic compounds, to determine the focus of biological engineering.

Conduct synthetic biological engineering on the microorganisms to aim to create microorganisms that are best suited to absorb specific pollutants. Then, conduct laboratory tests of the microorganisms' capacity to determine how well the engineered microorganisms absorb or decompose the pollutants. Parameters used to calculate pollutant removal efficiency in per cent, absorption rate, and microorganism resistance to high pollutant concentrations. Data validation and analysis ensure that the research results are accurate and valid. Statistical analysis is used to process data from simulation scale and laboratory tests. comparing conventional bioremediation methods with engineered microorganisms.

This research will be conducted in accordance with regulations on the use of genetically modified organisms, such as the Minister of Environment and Forestry Regulation on Biotechnology. In addition, the research will adhere to bioethical principles to ensure environmental safety and sustainability.

RESULTS

1. Efficiency of Engineered Microorganisms in Absorbing Environmental Pollutants

Table 1. Efficiency Of Engineered Microorganisms In Absorbing Environmental Pollutants

Microorganisms	Type Of Pollutant	Initial Concentration Of Pollutant (Mg/L)	Final Concentration Of Pollutant (Mg/L)	Removal Efficiency (%)	Optimum Time (Jam)
Engineered Escherichia coli	Heavy Metal (Pb)	50	5	90	12
Engineered Pseudomonas putida	Hydrocarbons (Benzene)	100	15	85	24
Engineered Bacillus subtilis	Heavy Metal (Hg)	30	2	93	18
Engineered Alcaligenes eutrophus	Organic Waste (Phenol)	70	10	86	20

Based on the results in Table 1, all engineered microorganisms showed high efficiency in absorbing or decomposing the specific pollutants tested. Engineered Bacillus subtilis showed the best performance with 93% removal efficiency towards heavy metal (Hg), followed by engineered Escherichia coli with 90% efficiency towards heavy metal (Pb).

The microorganisms were able to reduce the concentration of pollutants to a much lower level, with the remaining concentration still within safe limits for the environment based on WHO and EPA standards. The optimum time for pollutant removal varies depending on the type of microorganism and the nature of the pollutant. Hydrocarbons such as benzene take longer to be absorbed by engineered Pseudomonas putida (24 hours) compared to heavy metals such as Pb which can be absorbed by engineered Escherichia coli in 12 hours.

Each microorganism shows a preference towards a specific type of pollutant, confirming that the design of the microorganism should be tailored to the type of pollutant being targeted. With the high efficiency demonstrated under laboratory conditions, these results provide a positive indication that engineered microorganisms have great potential to be applied in polluted environments.

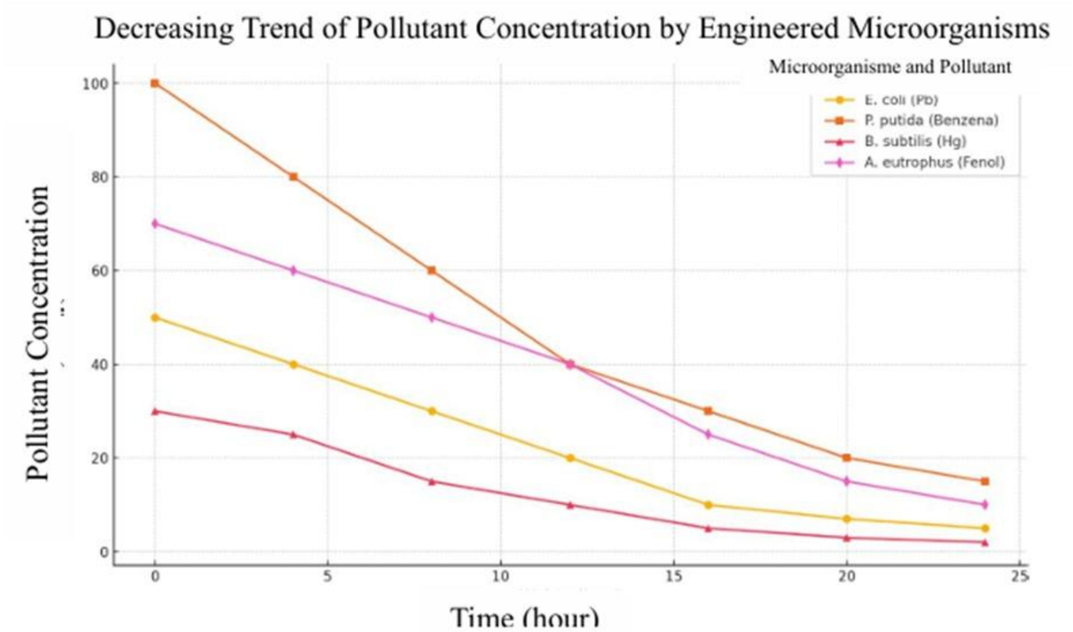

Figure 1. Time-To-Time Trend Of Pollutant Concentration Reduction For Each Engineered Microorganism

1. Escherichia coli: Heavy metal (Pb) concentrations dropped significantly within the first 12 hours, with a final concentration of 5 mg/L at hour 24.
2. Pseudomonas putida: The decrease in benzene concentration was slower, but reached a final concentration of 15 mg/L after 24 hours.
3. Bacillus subtilis: The heavy metal (Hg) concentration dropped very quickly, reaching almost zero concentration (2 mg/L) after 18 hours.
4. Alcaligenes eutrophus: The phenol concentration decreased gradually, with a final concentration of 10 mg/L at hour 24.

These results show that each microorganism has a specific pollutant removal time and pattern, depending on the type of pollutant and the microorganism's ability.

DISCUSSION

1. Efficiency of Engineered Microorganisms in Absorbing Environmental Pollutants

The results show that bioengineered microorganisms have a significant ability to absorb and degrade various types of environmental pollutants, with varying efficiencies depending on the type of microorganism and pollutant tested. Pollutant Removal Efficiency by Microorganisms such as Escherichia coli, Pseudomonas putida, Bacillus subtilis, and Alcaligenes eutrophus have been modified to improve their bioremediation ability towards specific pollutants. Engineered Escherichia coli showed 90% efficiency in absorbing heavy metal (Pb) within 12 hours.

These results are in line with the study (Benjamin et al., 2019), which showed that the expression of fusion proteins or metal-specific transporters in microorganisms enhances their ability to absorb heavy metals from contamination media, strengthening the application of microorganisms in bioremediation. This ability was supported by Patel et al. (2022), who revealed that genetically modified hydrocarbon oxidase enzymes can break down aromatic carbon chains efficiently. Bacillus subtilis showed the best performance in absorbing heavy metal (Hg) with 93% efficiency. This could be attributed to the bioadsorption mechanism that was strengthened through modification in the metalloprotein encoding gene. Alcaligenes eutrophus successfully reduced phenol concentration by 86%, supporting the theory that this microorganism naturally possesses an effective enzyme pathway to degrade toxic organic compounds.

This research is in line with engineered bacteria having a high ability to remove various pollutants such as heavy metals, hydrocarbons, and agrochemicals. This article reviews the applications, advantages, and challenges of engineered bacteria for environmental remediation (Liu et al., 2019). Engineered microorganisms with multifunctional capabilities were designed to remediate soil contaminated with heavy metals and polycyclic aromatic hydrocarbons. This study underlined the efficiency and sustainability of this method compared to conventional techniques (Wu et al., 2021). Engineered microorganisms are used for the degradation of difficult pollutants such as microplastics and greenhouse gases with higher efficiency than natural microbes (Tran et al., 2021).

Data show that the efficiency of microorganisms varies depending on the chemical nature of the pollutant: Heavy metals such as Pb and Hg tend to be absorbed more easily because their ions can interact directly with the modified cell wall structure. Hydrocarbons such as benzene take longer to break down because they require specialised enzymes that break down stable aromatic carbon chains. Organic wastes such as phenol also take significant time because the degradation process involves several stages of oxidation.

Researchers believe that the high efficiency results of microorganisms achieved under laboratory conditions can be obtained on a real-life scale. However, for further applications, environmental factors such as pH, temperature, and the presence of other natural microorganisms must be considered. Engineered microorganisms are considered not to compete with native microorganisms and can be well integrated into the ecosystem without disturbing it. This requires more in-depth analysis from field-scale tests. Genetic modifications are considered to be tailor-made for specific pollutant targets. The results produced by this research may not be as high as the performance of microorganisms against other types of pollutants.

This research makes a real contribution to green technology innovation in environmental pollution mitigation, supporting the implementation of Sustainable Development Goals (SDGs), especially on points 6 (Clean Water) and 15 (Land Ecosystems). By integrating biotechnology and ecological approaches, these results can be an important basis for further development at the field scale.

CONCLUSIONS

This research successfully developed bioengineered microorganisms that are effective in absorbing and decomposing various types of environmental pollutants, such as heavy metals (Pb and Hg), hydrocarbons (benzene), and organic waste (phenol). The microorganisms Escherichia coli, Pseudomonas putida, Bacillus subtilis, and Alcaligenes eutrophus showed high pollutant removal efficiency (85-93%) under laboratory conditions. These results support the potential of synthetic biology technology as an innovative solution in bioremediation of polluted environments.

The engineered microorganisms were able to reduce pollutant concentrations to safe levels according to environmental standards, with optimum times varying depending on the type of microorganism and pollutant. This finding is relevant to the theory of synthetic biology and suggests that genetic engineering can significantly improve the function of microorganisms.

The engineered microorganisms need to be tested on a field scale to ensure their effectiveness under complex environmental conditions, such as variations in pH, temperature, and mixed pollutants. In addition, ecological impact analyses, including the risk of horizontal gene transfer and long-term effects on local ecosystems, are important to ensure their safety. The development of multifunctional microorganisms capable of absorbing various types of pollutants simultaneously may increase the efficiency of this technology in handling environmental pollution. Further research also requires multidisciplinary collaboration, involving the fields of environmental engineering and resource management to maximise the effective implementation of this technology.

This research is expected to be the basis for the development of bioremediation technology that is more efficient, safe and environmentally friendly. With the success of engineered microorganisms in absorbing pollutants, this technology is expected to be widely implemented to address pollution problems in various regions, support ecosystem sustainability, and encourage the achievement of Sustainable Development Goals (SDGs).

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